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# Dark Matter in Dwarf Galaxies: The First Dark Galaxy?

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**Abstract.** We present new H I observations of the high-velocity cloud (HVC) that we resolved near the Local Group dwarf galaxy LGS 3. The cloud is rotating, with an implied mass that makes it dark matter-dominated no matter what its distance from the Milky Way is. Our new, high-sensitivity Arecibo observations demonstrate that the faint H I features that we previously described as tidal tails are indeed real and do connect to the main body of the HVC. Thus, these observations are consistent with our original hypothesis of a tidal interaction between the HVC and LGS 3. We suggest that the HVC may be one of the missing dark matter satellites in the Local Group that are seen in Cold Dark Matter numerical simulations but have not yet been identified observationally.

## 1. Introduction

The first hint of unusual goings-on in the neighborhood of LGS 3 came from Christian & Tully (1983), who mentioned that H I observations by Hulsbosch revealed that LGS 3 lies on the edge of a large cloud of gas (called HVC 127-41-330 by them) that contains a significant velocity gradient. However, with the $36'$ resolution of his Dwingeloo observations, Hulsbosch was apparently unable to draw any firm conclusions about the nature of this object. Over the next 17 years the situation remained murky as few observers paid attention to this part of the sky. The sole reference to the cloud during this period was in the HVC catalog of Hulsbosch & Wakker (1988), who assumed that it was part of LGS 3.

Three years ago the cloud was rediscovered by Blitz & Robishaw (2000) during their search for gas associated with Local Group dwarf spheroidals in the Leiden/Dwingeloo Survey (LDS) of Galactic Neutral Hydrogen (Hartmann & Burton 1997). Blitz & Robishaw (2000) pointed out the offsets in position and velocity between this cloud and the H I known to be directly associated with LGS 3 (Thuan & Martin 1979; Young & Lo 1997). They speculated that the cloud might have been ram-pressure stripped out of LGS 3 by hot gas in the halo of M31. They noted, however, that the velocity of the cloud should be less negative than the velocity of LGS 3 ($v_{\rm HVC} > -287$ km s$^{-1}$), which it is not ($v_{\rm HVC} \approx -330$ km s$^{-1}$). Like Hulsbosch, their ability to consider other possible origins for the cloud was limited by the low angular resolution of the LDS data.

Robishaw, Simon, & Blitz (2002) shed new light on this object with a high-resolution, wide-field H I map of the region made at Arecibo. These observations showed that the cloud is completely separate from LGS 3, demonstrating that it is indeed an HVC.

## 2. Discussion

The Robishaw et al. (2002) observations raised several pressing questions. What is the nature of the LGS 3 HVC? Are LGS 3 and the HVC actually located at the same distance, or is their apparent proximity just a chance alignment? Even though there is no H I connection between LGS 3 and the HVC, could the high-velocity gas be associated with LGS 3 in any way?

### 2.1. Distance of the HVC

In Robishaw et al. (2002) we pointed out that the probability of a chance superposition between a compact HVC and a dwarf galaxy — if they are completely unrelated objects — is rather low. Using the statistics of HVCs in the LDS (de Heij et al. 2002) and known Local Group dwarfs, we showed that the likelihood of an HVC being located less than $30'$ from a dwarf is $\sim 4\%$ in this area of the sky. Given such an angular coincidence, the probability of the velocities also matching within 50 km $s^{-1}$ is $\sim 20\%$, for a joint probability of less than 1%. This line of reasoning suggests, but does not prove, that the HVC and LGS 3 are physically associated.

A more powerful argument can be made based on the faint H I strips that our first Arecibo map revealed on either side of the HVC. These features appeared to be long, thin tails of gas that connect to the HVC. That appearance, along with their nearly symmetrical placement relative to the line between LGS 3 and the HVC, is a strong signal of a tidal interaction between the two objects. If this interpretation is correct, the HVC must be located physically close to LGS 3, at a distance of about 700 kpc from the Milky Way. This HVC would then be the first HVC known to lie more than $\sim 50$ kpc away.

### 2.2. HVC Rotation Curve

The HVC shows a surprisingly regular velocity gradient indicative of circular rotation. Robishaw et al. (2002) argued against the possibility of a chance alignment of two separate clouds moving at slightly different velocities, so if the gradient is *not* due to rotation, the only alternative is shear. A simple timing calculation shows that this explanation is unlikely. The cloud currently has a radius of about 3 kpc (D/1 Mpc), where D is the distance of the HVC. The velocity gradient is 15 km $s^{-1}$, which would correspond to an expansion velocity of 7 km $s^{-1}$. At that expansion rate, the time for the cloud to reach its current size is $4 \times 10^8$ (D/1 Mpc) yr. In this scenario, distances of less than 100 kpc are highly implausible — the HVC would have to be extraordinarily young, and even then the nearest possible progenitors, the Magellanic Clouds, are too far away for the HVC to have reached its present position at any reasonable velocity. At 700 kpc the lifetime of the cloud is still uncomfortably shorter than a Hubble time, and the lack of a credible progenitor object is equally severe. We conclude that the velocity gradient is almost certainly due to rotation.

The rotation curve of the HVC, as measured by Robishaw et al. (2002), is symmetric and flattens out at a radius of about $10'$ (see Fig. 1). The total mass derived from the rotation curve is larger than the H I mass for any reasonable distance, implying that the HVC is dark matter-dominated. At 700 kpc, 82 % of the mass is in dark matter; at 50 kpc, 99 % of the mass is dark. The HVC

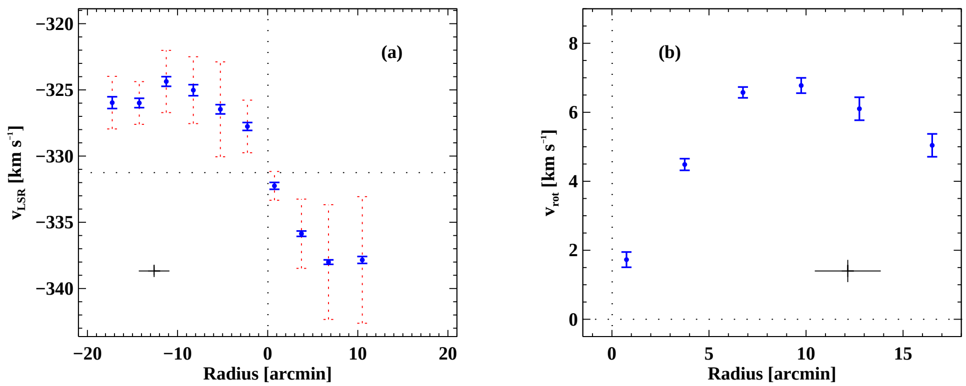


Figure 1. (a) Major axis rotation curve of the HVC. The blue (red) error bars represent the uncertainties in the Gaussian fits (the scatter in the velocity field perpendicular to the major axis). Removing this rotation curve from the velocity field yields a residual field with an rms of 3 km s$^{-1}$. (b) The rotation curve folded about the point of maximum symmetry. After a solid-body rise out to 10′, the rotation curve turns over and begins to decline. The error bars are the 1 $\sigma$ uncertainties of the weighted average of the Gaussian fits. The crosses indicate the velocity and spatial resolution of our measurements.

can only be dynamically dominated by luminous material if its distance is $\gtrsim 2$ Mpc, which is extremely unlikely.

### 2.3. New Observations

In August 2002, we used another Arecibo observing run to make a new, more sensitive map of LGS 3 and the HVC. This map, displayed in Figure 2, confirms all of the features seen in our original data. The tidal tails are now visible in detail, and their connection to the main body of the HVC is evident. The tails are somewhat more extended than could be seen in the first map, and additional observations over a wider field have revealed that the southwest tail continues on beyond the edge of the map shown in Figure 2. The new data are fully consistent with the scenario proposed by Robishaw et al. (2002) of a tidal interaction between the HVC and LGS 3.

## 3. Conclusions

Given these findings, what can we conclude about the nature of this HVC? We have presented several arguments that it is probably located hundreds of kiloparsecs away, most likely at 700 kpc. The HVC appears to be undergoing a tidal interaction with LGS 3, which is stripping away a substantial portion of its neutral gas. If the HVC is in the Local Group it is dark matter-dominated, regardless of its exact distance. And, it does not contain any stars (Robishaw et al. 2002). This set of properties is exactly what is expected of the missing

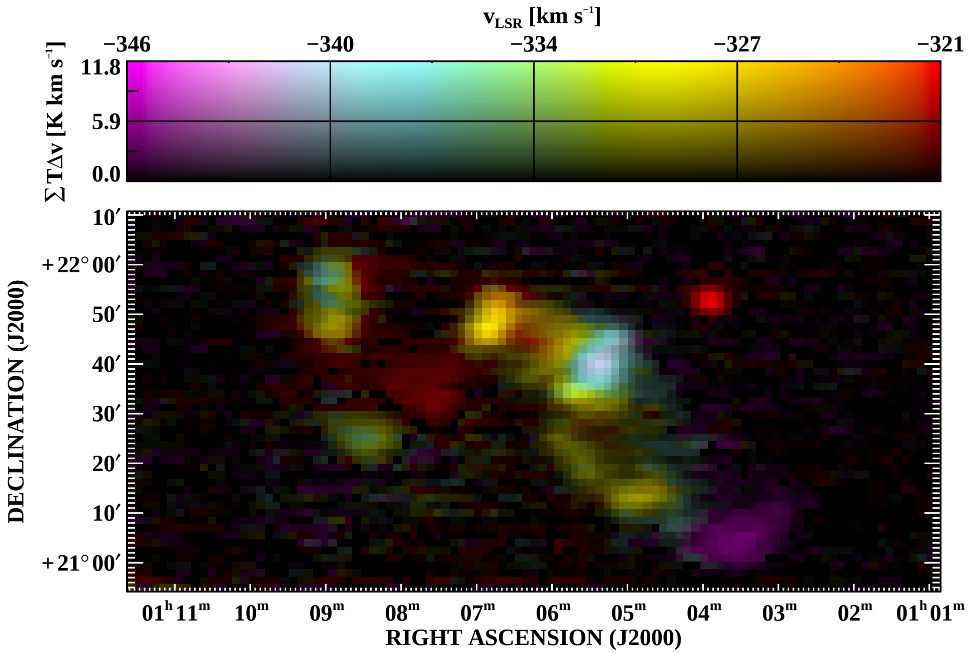


Figure 2. High-sensitivity, wide-field H I map of the region containing the HVC and LGS 3. Brightness represents integrated intensity and the color scale represents velocity. LGS 3 is the red source in the upper right; the HVC is the double-lobed object above the center of the map. The faint features to the east and southwest of the HVC that were barely visible in our original data now stand out clearly. Both are (mostly) spatially continous structures that connect to the main body of the HVC, supporting our interpretation of them as tidal tails that are being torn off of the HVC by LGS 3.

dark matter satellites that are predicted by simulations. We propose that this HVC is the first observed representative of this population of missing objects.

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